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GROUND SHOCK ATTENUATION FOR DEEP BASING IN SATURATED LAYERED G-ETC(U)

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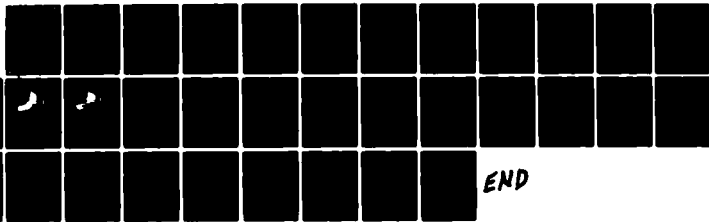
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# GROUND SHOCK ATTENUATION FOR DEEP BASING IN SATURATED LAYERED GEOLOGIES

California Research & Technology, Inc.  
6269 Variel Avenue  
Woodland Hills, California 91367

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  Finite difference code calculations were conducted using the 2-D CRALE code to determine if distinct stratigraphic layering would substantially contribute to attenuation of stresses and motions at depth beneath large nuclear bursts over saturated geologies. Three geologies were examined: In Case 1, there were five distinct layers of soft rocks above the bedrock at 2300 ft. In Case 2, layers were homogenized to eliminate diffraction at interfaces. Case 3 was the same as Case 1, but with 1% hysteretic compaction in layers above the bedrock to simulate air entrainment. The burst was represented as a shallow-buried		

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20. ABSTRACT (Continued)

isothermal sphere containing 7.5 Mt of energy.

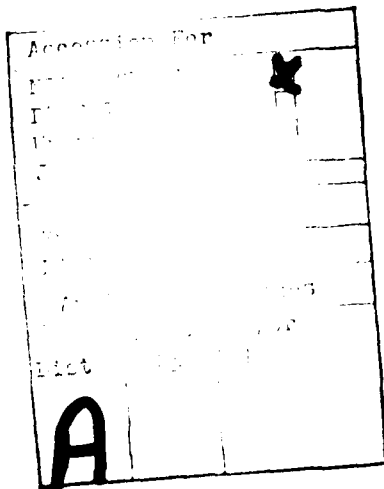
The results show only minor differences between waveforms and peak stresses for the three cases. Peak stresses attenuated approximately as the square of the depth, i.e.,  $\sigma_{\max} \propto D^{-2}$  (similar to attenuation observed in hard rock). Layering in media above the bedrock (Case 1) reduce stresses in the bedrock by only 10-15% (as compared with the homogenized media in Case 2). In the three cases, stresses above 1.5 kb were experienced to depths between about 3200 and 3800 ft.

It is concluded that the effects of typical layering in saturated sedimentary soft rock layers will not substantially reduce peak stresses beneath near-surface bursts. Deep base facilities in such geologies would probably need to be placed at depths equivalent to those required in hard rock.

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# TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
	LIST OF ILLUSTRATIONS . . . . .	2
1	INTRODUCTION AND SUMMARY. . . . .	3
	1.1 BACKGROUND . . . . .	3
2	APPROACH. . . . .	5
	2.1 GEOLOGIC PROFILES. . . . .	5
	2.2 SOURCE CONDITIONS. . . . .	5
	2.3 NUMERICAL METHOD . . . . .	8
3	RESULTS . . . . .	9
	3.1 DEVELOPMENT OF GROUND MOTIONS. . . . .	9
	3.2 STRESS, VELOCITY, AND DISPLACEMENT WAVEFORMS BENEATH BURST. . . . .	13
4	CONCLUSIONS . . . . .	20
	REFERENCES. . . . .	22
	APPENDIX - GEOLOGY AND MATERIAL MODELING. . . . .	23



## LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1     Geologic Profiles for Numerical Solutions . . . . .	6
2     Material Properties Profiles used in Numerical Solutions . . . . .	7
3     Velocity Vector Field at 78 msec in Case 1 - Basic Layered Profile, Totally Saturated. . . . .	10
4     Velocity Vector Field at 123 msec in Case 1 - Basic Layered Profile, Totally Saturated. . . . .	11
5     Velocity Vector Field at 113 msec in Case 2 - Homogenized Layers between 410 ft and 2300 ft . . . .	12
6     Stress, Velocity, and Displacement Time Histories Near Axis at 1300 ft Depth (395 m). . . . .	14
7     Stress, Velocity, and Displacement Time Histories Near Axis at 2460 ft Depth (750 m) in the Bedrock . .	15
8     Peak On-Axis Stress vs Depth. . . . .	16
9     Peak Stress Contours. . . . .	18
10    Peak On-Axis Displacement vs Depth. . . . .	19
A-1   Stress Profile at 2130 ft (650 m) Obtained from 1-D Spherical Analyses to Assess Effects of Homogenized Properties on Waveforms Incident to the Bedrock Interface . . . . .	26

## SECTION 1.

### INTRODUCTION AND SUMMARY

#### 1.1 BACKGROUND

Deep basing concepts attempt to increase the survivability of strategic reserve forces or command systems by placing such facilities several thousand feet underground, depending on attenuation in the geologic media to reduce the ground shock from nuclear bursts on or near the surface to acceptable levels.

In homogeneous media, the depths required to attenuate peak over stresses to a given level have been estimated by Cooper<sup>1</sup> from underground test data:

$$\text{Hard rock:} \quad W^{1/3} \sigma_{\max}^{1/2} \lesssim D \lesssim 2W^{1/3} \sigma_{\max}^{1/2} \quad (1)$$

$$\text{Soft rock:} \quad 0.4W^{1/3} \sigma_{\max}^{1/2} \lesssim D \lesssim 0.8W^{1/3} \sigma_{\max}^{1/2} \quad (2)$$

where

$W$  = yield (Mt) of a shallow-buried burst

$\sigma_{\max}$  = peak over stress level (kb)

$D$  = depth (kft)

For a shallow burst of  $W = 7.5$  Mt and a peak over stress level of  $\sigma_{\max} = 1.5$  kb, the estimated depths are:

In hard rock:  $D = 1600-3200$  ft (500-1000 m)

In soft, dry rock:  $D = 650-1300$  ft (200-400 m)

An optimum deep basing geology might consist of a relatively thin hard rock surface layer (to discourage use of earth penetrators), over a thick, fairly uniform layer of dry, porous soft



rock (to provide rapid shock attenuation), over a hard bedrock (to provide structural resistance). A geology of this nature can be found, for example, in Idaho and eastern Oregon, where a basalt flow overlies a thick pumice layer over a hard bedrock<sup>2</sup>. Suitable geologies without the surface rock are common in the Southwest.

The occurrence of dry, porous sites with promising shock attenuation characteristics (with or without the surface rock) does not, however, assure that such sites are available nor desirable for deep basing. Alternative geologies may be preferable for operational or other practical reasons. The existence of support facilities, for example, may make it desirable to locate deep base facilities at or near existing Minuteman sites, providing that the deep facility is survivable in Minuteman geologies. These typically consist of multiple layers of shales and softer sedimentary rocks over a hard basement at 2000-4000 feet (600-1200 m). Unfortunately, the water table is generally shallow, and ground shock attenuation through saturated porous media is more gradual than in dry porous media. There is some question whether Minuteman geologies, or any other saturated porous geologies, are practical for deep basing, since stresses sufficient to destroy structures (say  $\sigma_{\max} > 1.5 \text{ kb}$ ) may be experienced to unacceptably large depths.

The distinct stratigraphic layering at typical Minuteman sites, however, may provide an additional mechanism to reduce the stresses at depths. There are fairly large impedance mismatches between layers which will produce some lateral diffraction of stress waves, leading to more rapid stress wave attenuation with depth. Whether or not the degree of diffractive attenuation in such geologies will be sufficient to reduce the ground shock environment at practical depths to tolerable levels is the key technical question addressed herein.

## SECTION 2.

### APPROACH

#### 2.1 GEOLOGIC PROFILES

Three finite difference calculations were performed of the stress wave propagation and ground motions beneath a 7.5 Mt shallow-buried burst, using the geologic profiles in Figure 1, and the properties in Figure 2. The detailed material models are described in the Appendix. The basic profile (Case 1) contains several layers of saturated, soft sedimentary rock above a hard bedrock. Its dimensions and properties were constructed using data provided by J. Zelasko of Waterways Experiment Station<sup>3</sup>.

In Case 1, the major geologic layers were separately defined in the computational grid, and all the layers were totally saturated (i.e., there was no air-filled porosity).

In Case 2, layers between the surface layer and the bedrock were homogenized into a single layer having weighted-average properties. Comparisons between the layered vs homogenized models in Case 1 vs Case 2 permit assessment of the effects of reflection and diffraction processes at interfaces upon stress attenuation beneath the burst.

Even in nominally-saturated porous media, there is probably a small amount of air entrapped in cracks and pores. To assess the possible importance of such air-filled porosity, 1% hysteretic compaction in the soft rock layers above the bedrock was specified in Case 3.

#### 2.2 SOURCE CONDITIONS

In selecting the burst condition, it was assumed that a 30-Mt surface burst would be a credible threat against a deep-based facility. To avoid the need for calculating the details of energy coupling from such a surface burst, it was further assumed that a

Case 1. Basic profile of layered, saturated, soft sedimentary rocks over bedrock. Layers were explicitly modeled.

Case 2. Same geology but layers 2-4 were homogenized using weighted average properties.

Case 3. Same as Case 1, but with 1% hysteretic compaction in all layers above bedrock to simulate air-filled voids.

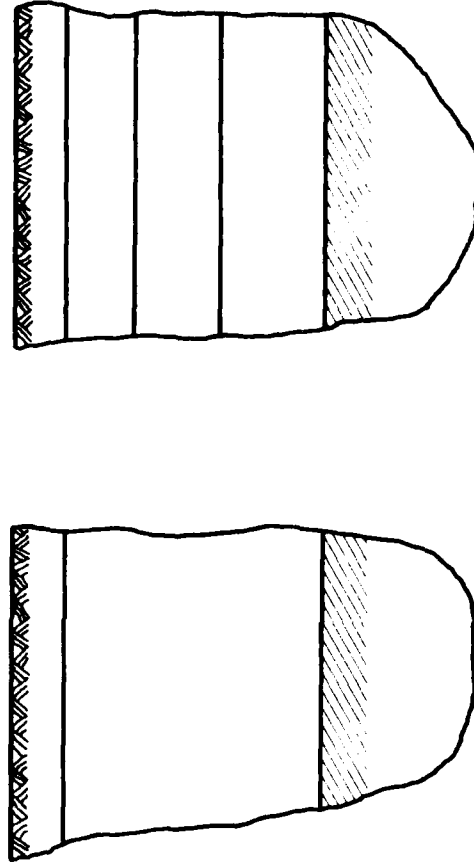
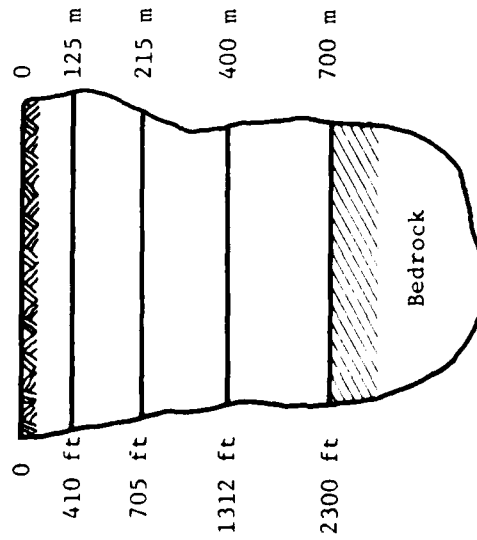


Figure 1. Geologic Profiles for Numerical Solutions.

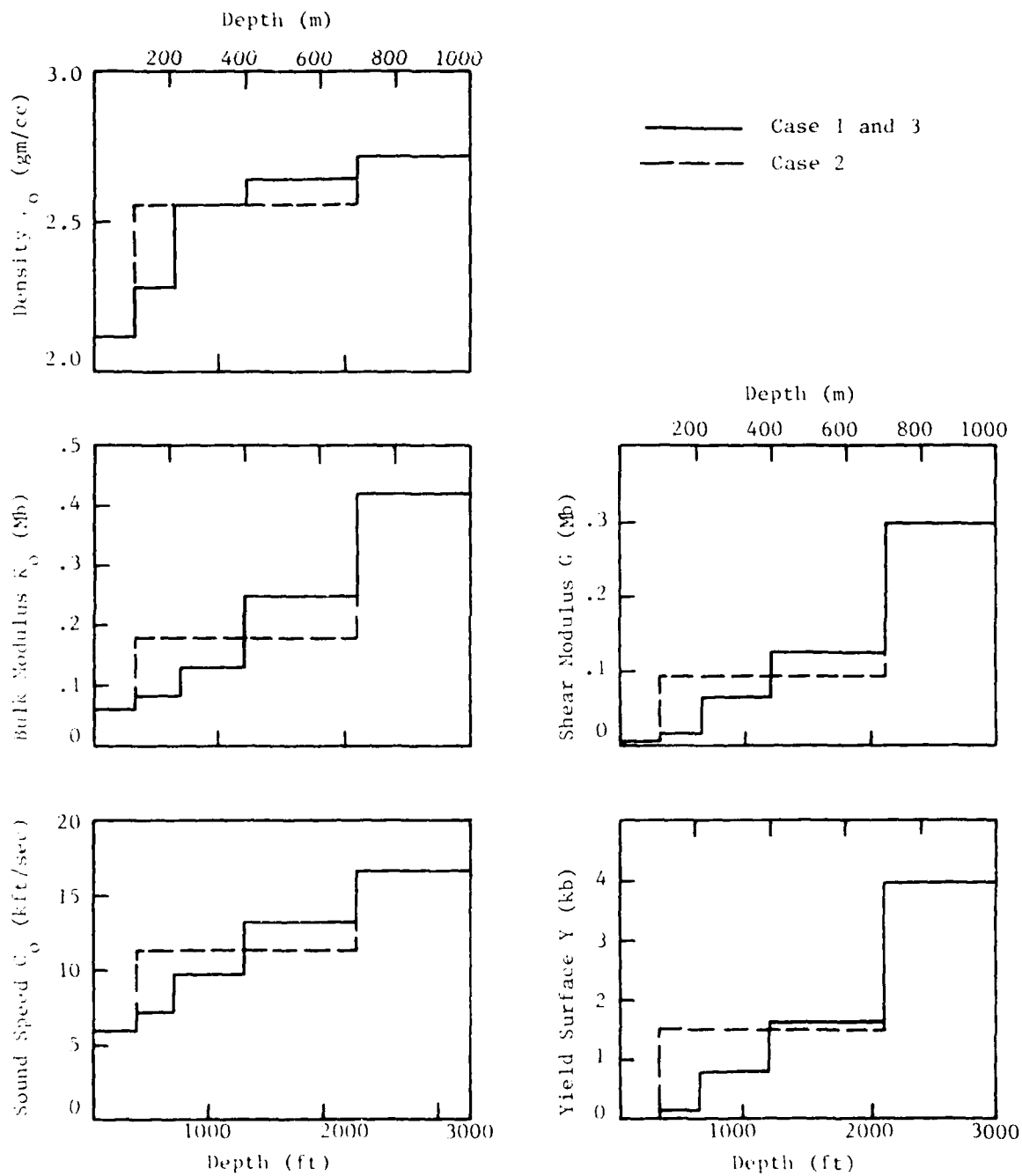


Figure 2. Material Properties Profiles used in Numerical Simulations.

surface burst produces the same ground motion effects as a shallow-buried burst of 1/4th the yield<sup>2</sup>. The source was therefore represented as 7.5 Mt of energy uniformly distributed in a 6-m radius sphere of Layer 1 material centered 10 m below the surface. This gave an initial pressure of 140 Mb. The effects of airblast on the surface were modeled by application of the Brode overpressure function to the upper boundary of the grid, using  $W = 7.5$  Mt.

### 2.3 NUMERICAL METHOD

The three 2-D problems were run using the CRALE (California Research Arbitrary Lagrangian-Eulerian) code, an axisymmetric finite-differencing time-marching program. In this code, the grid motion algorithm allows the user to rezone the grid points *each cycle* in order to maintain reasonable zone sizes and shapes. For the problems in this study, the initially vertical lines were required to remain vertical. The initially horizontal interfaces separating layers were treated as Lagrangian grid lines, i.e., the grid lines were displaced as the interfaces deformed. Between these interfaces, the initially horizontal grid lines moved so as to remain equally spaced. Thus, material was transported across grid lines within each layer, but not across interfaces. Material at the ground surface moving upward at high velocity was allowed to pass through the top of the grid.

## SECTION 3.

### RESULTS

#### 3.1 DEVELOPMENT OF GROUND MOTIONS

Development of the ground motions is illustrated by the velocity vector fields in Case 1 at 78 and 123 msec after the burst. By 78 msec (Figure 3), the main shock front is approximately 1000 ft from the source and the peak stress is about 7.5 kb. At this time, the layering does not appear to significantly affect the propagation of the diverging wave. By 123 msec (Figure 4), the main shock has reached a depth of about 1500 ft and the peak stress has attenuated to about 4 kb. The layering is still not significantly perturbing the shock front, but there is some rotation of particle velocities behind the shock just below the 705 ft interface, due to differences in the yield condition in materials above and below that interface.

The velocity field at 113 msec for Case 2, in which layers between 410 ft and the bedrock at 2300 ft were homogenized, show a very pronounced interface effect at 410 ft depth (Figure 5). This is because the homogenization of properties for layers below 410 ft led to a relatively large mismatch of properties across that interface (see Figure 2). In particular, stresses were still sufficient to cause yielding above that interface (where the Mises yield surface,  $Y = 0.1$  kb), but were insufficient to produce yielding in the much stronger material below the interface (in which  $Y = 1.5$  kb). The result is a discontinuity in particle velocities. In addition, the substantially higher wave velocity beneath the interface led to the outrunning condition which is evident in Figure 5. These phenomena at the shallow interface did not, however, substantially affect the stresses and ground motions at depth.

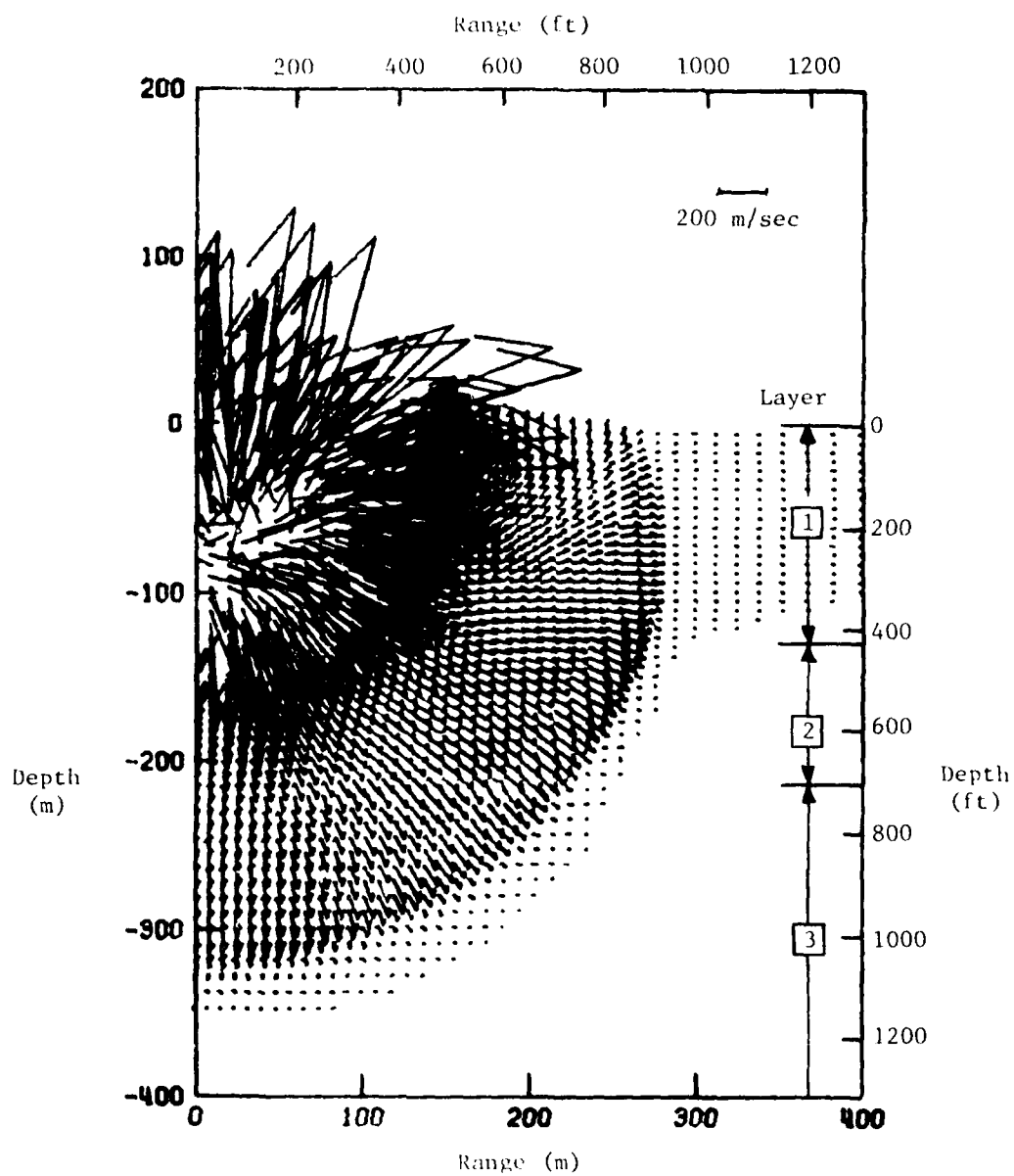


Figure 3. Velocity Vector Field at 78 msec in Case 1 - Basic Layered Profile, Totally Saturated

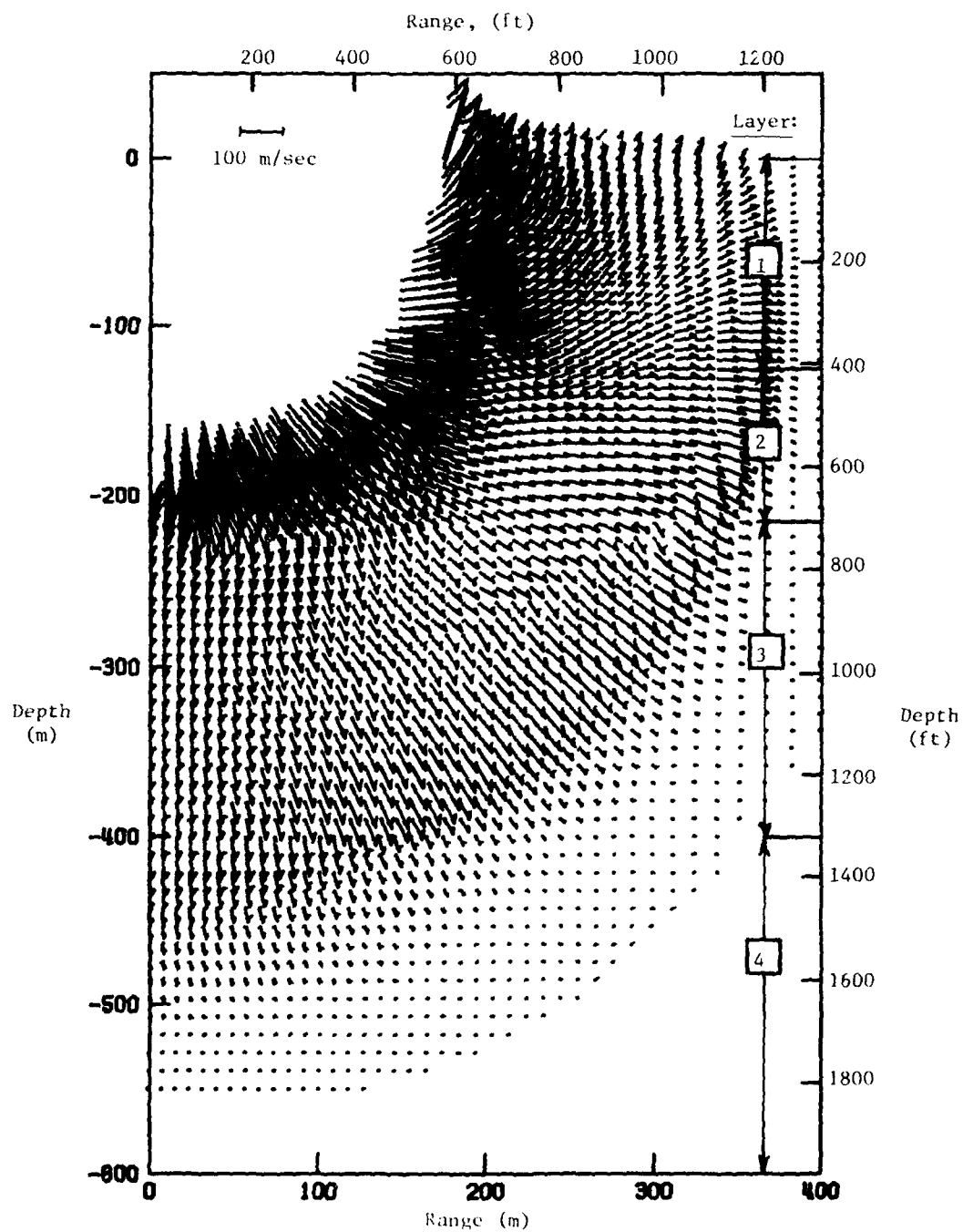


Figure 4. Velocity Vector Field at 123 msec in Case 1 - Basic Layered Profile, Totally Saturated. (Vectors in vaporized region near source are suppressed.)



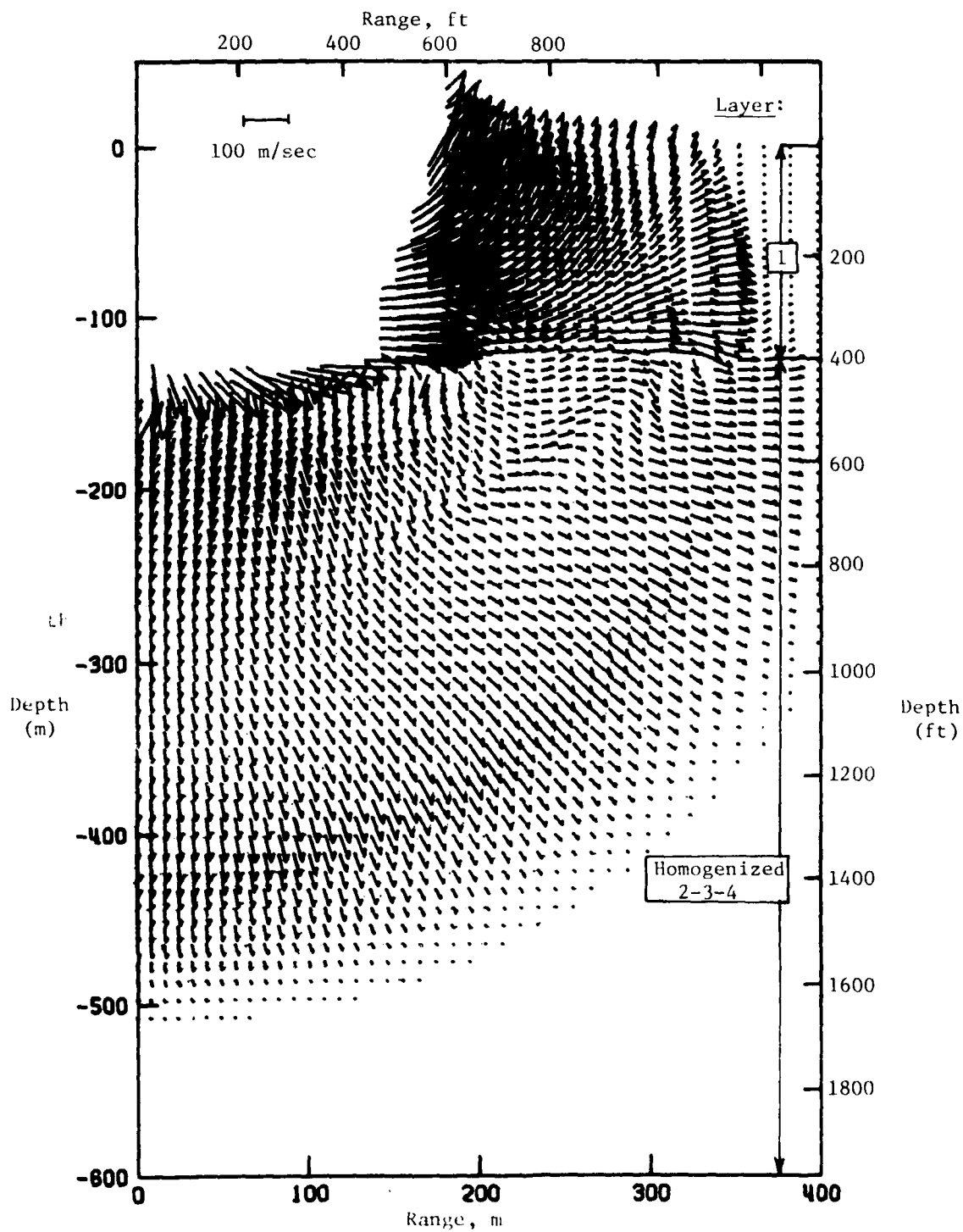


Figure 5. Velocity Vector Field at 113 msec in Case 2 - Homogenized Layers between 410 ft and 2300 ft. (Vectors in vaporized region near source are suppressed.)

### 3.2 STRESS, VELOCITY, AND DISPLACEMENT WAVEFORMS BENEATH BURST

The similarity of basic ground motions beneath the burst in the three geologic profile cases is illustrated by comparing the near-axis stress, velocity, and displacement histories in the soft rock at 1300 ft depth and in the bedrock at 2460 ft depth.

At the station in the soft rock (Figure 6), there are only minor differences between the waveforms. At the deeper station (Figure 7), the effects of the large mismatch of properties at the bedrock interface in the homogenized profile (Case 2) results in a sharper, somewhat stronger stress pulse entering the bedrock. Peak displacements in the homogenized profile, by contrast, are somewhat lower than in the corresponding layered profile (Case 1). In the layered geology with 1% hysteretic compaction (Case 3), stresses and velocities drop more quickly, due to the higher velocity of relief waves in the hysteretic model. Displacements in Case 3 are therefore smaller.

Peak stresses vs depth for near-axis locations are shown in Figure 8. *Differences between the three cases are relatively small at all depths.* At depths down to the bedrock interface at 2300 ft, the calculated stresses attenuate approximately as the square of the depth, i.e.,  $\sigma_{\max} \propto D^{-2}$ . In the layered geology (Case 1), stresses incident upon the bedrock are slightly *higher* than in the homogenized geology (Case 2), but the smoother match of properties across the softrock-bedrock interface in Case 1 results in lower stresses entering the bedrock, and this difference persists. Thus layering in media above the bedrock (as in Case 1) reduces the stresses in the bedrock (as compared with homogeneous media), but only by 10-15%.

The introduction of 1% hysteretic compaction to account for a small degree of air-filled porosity does not significantly affect the peak stress vs depth.

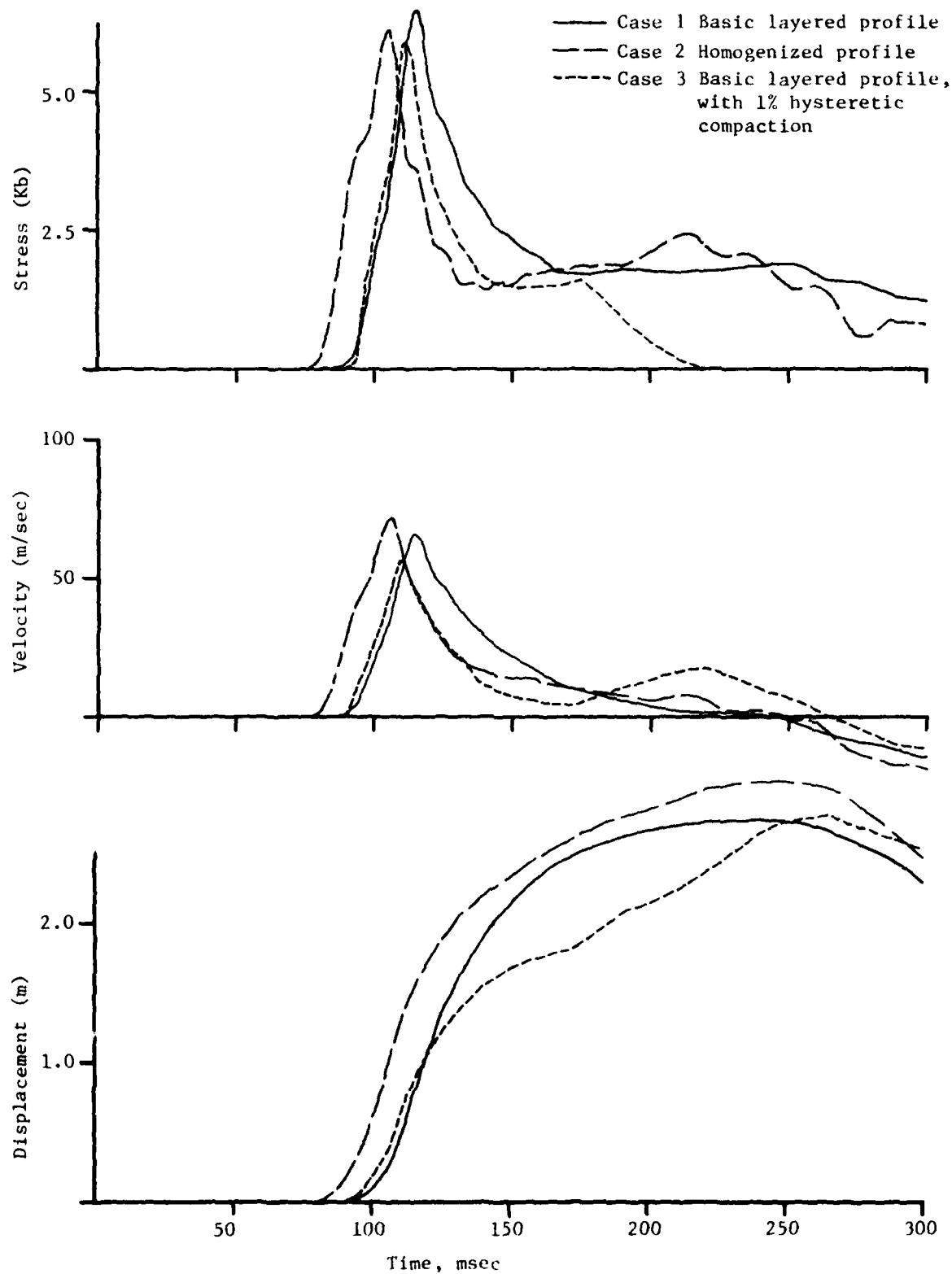


Figure 6. Stress, Velocity, and Displacement Time Histories Near Axis at 1300 ft Depth (395 m).

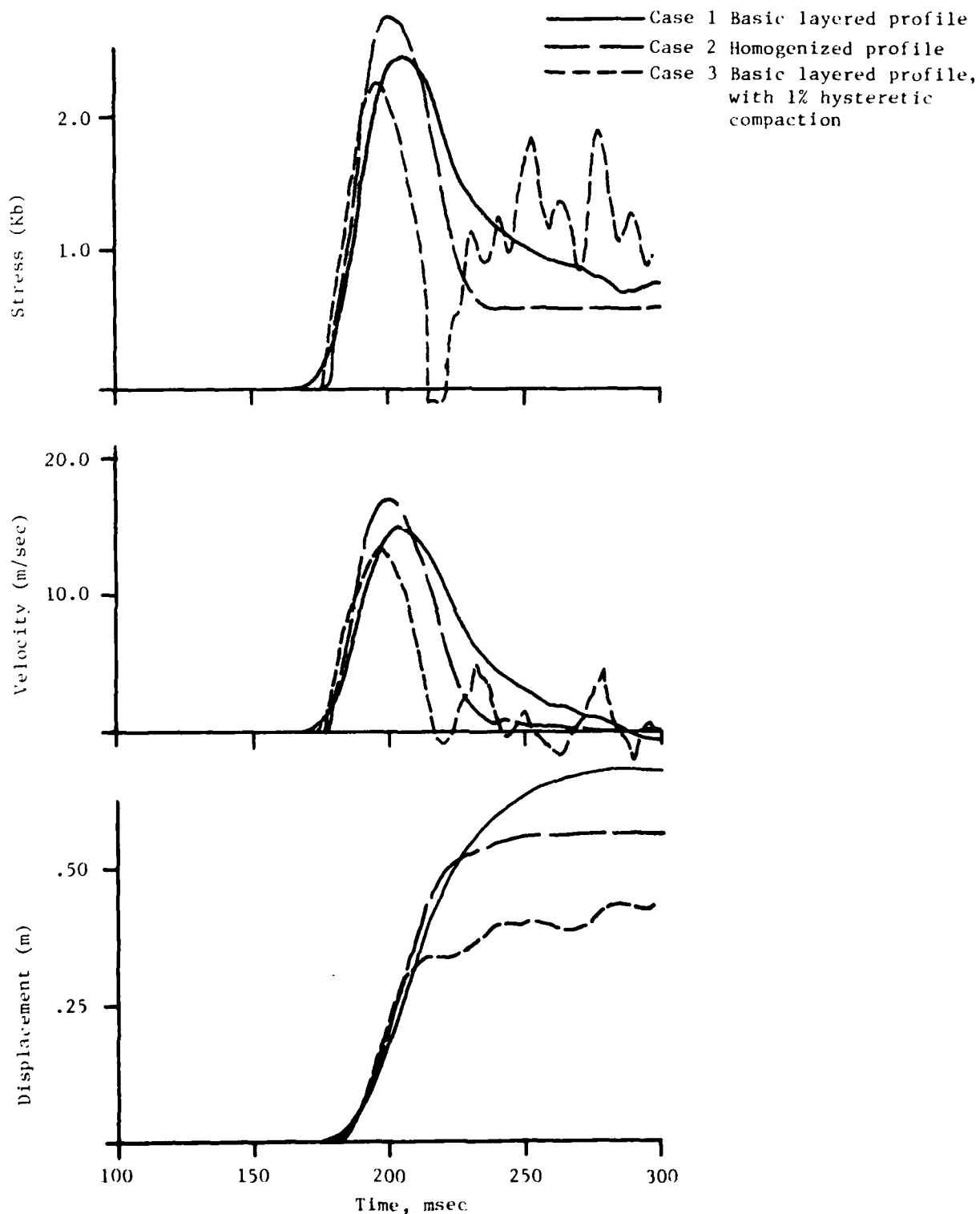


Figure 7. Stress, Velocity and Displacement Time Histories Near Axis at 2460 ft Depth (750 m) in the Bedrock.

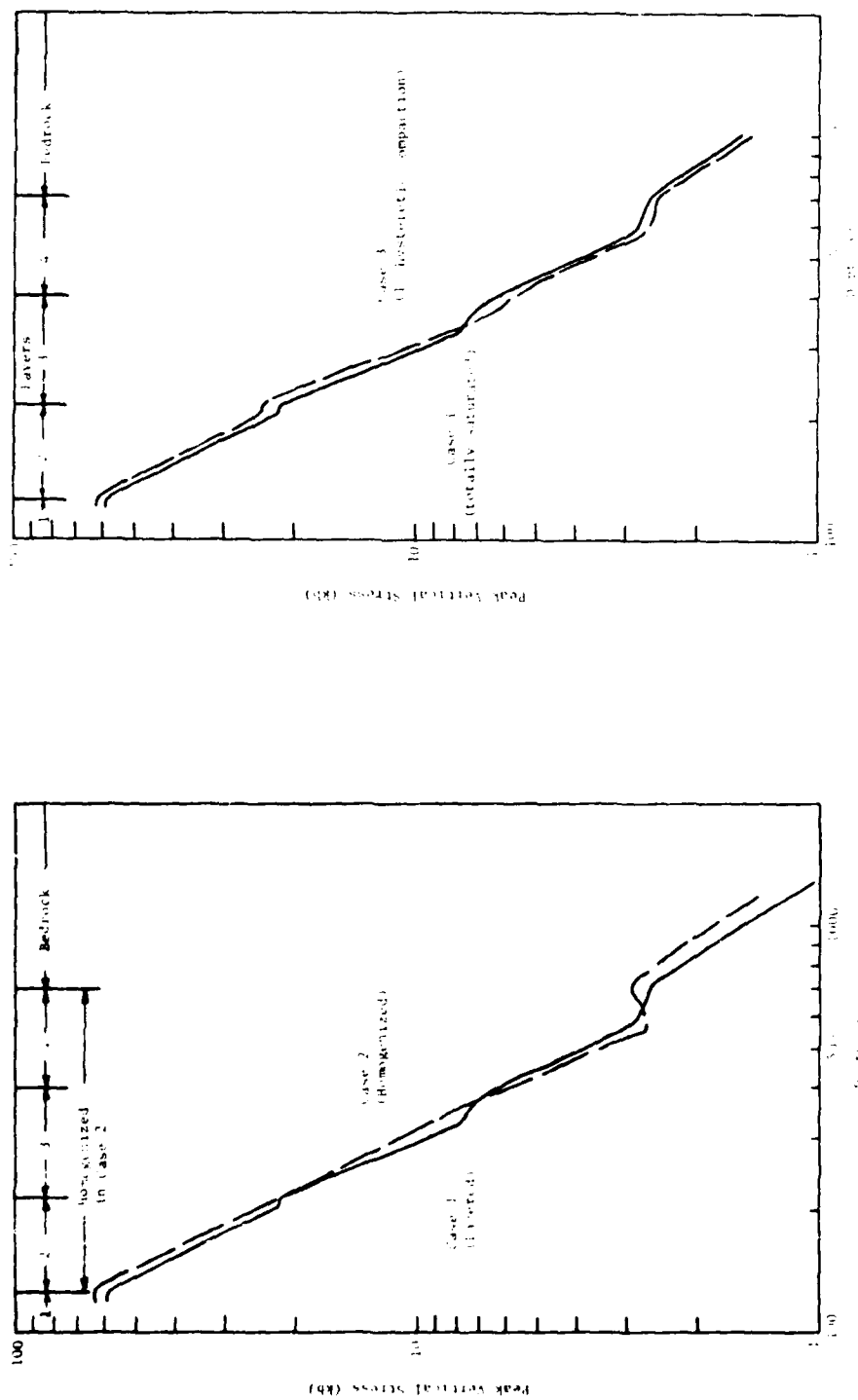


Figure 8. Peak On-Axis Stress vs Depth.

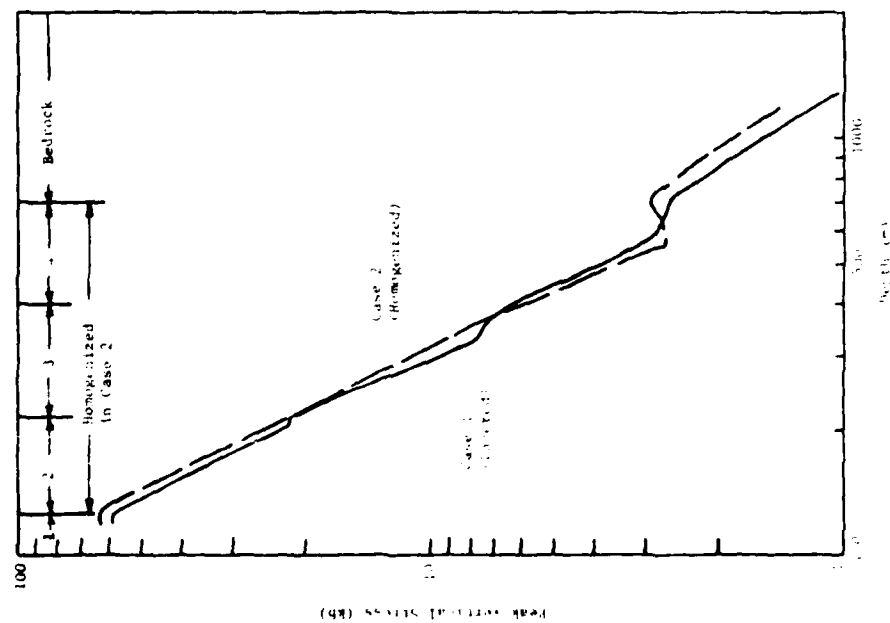
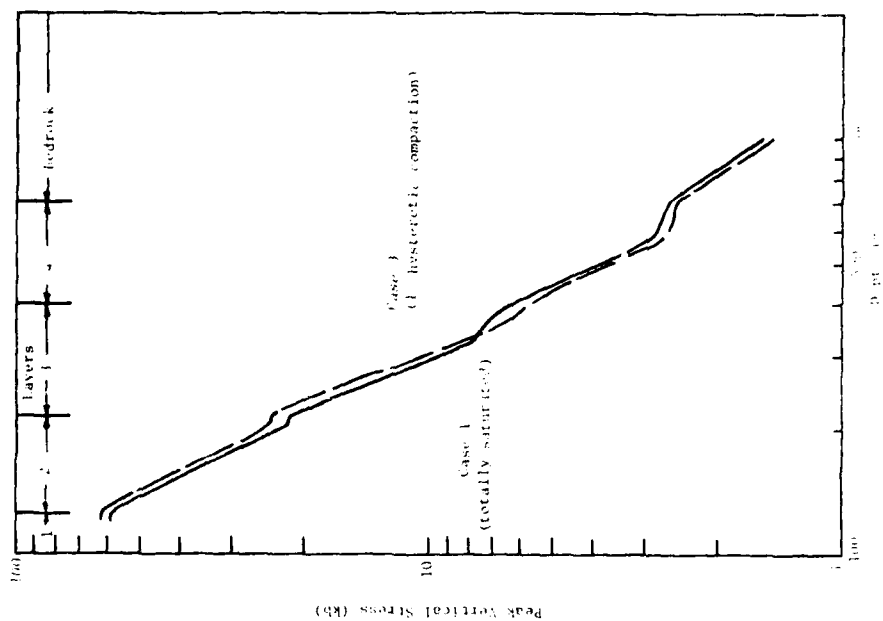


Figure 8. Peak On-Axis Stress vs Depth.

Figure 9 shows peak stress contours for the three cases. Comparison of Cases 1 and 2 shows that layering reduces the maximum depths and ranges in the bedrock at which damaging peak stresses are experienced, but not by significant margins. For example, when there is an unlayered medium above the bedrock, 1.5 kb peak stresses are experienced to a maximum of 2705 ft depth, and to a maximum range (from the axis) in the bedrock of 1310 ft. When there is layered media above the bedrock, 1.5 kb peak stresses extend only to 3345 ft depth, and to 1150 ft range in the bedrock. With 1% hysteresis in the layered media, the maximum depth is further reduced to 3180 ft, and the maximum range in the bedrock to 1000 ft.

Figure 10 shows peak displacements. The differences are small, except in the 1% hysteretic geology (Case 3), where much smaller displacements occur in the bedrock. This is because the unloading arrives relatively sooner in the hysteretic geology, thereby shortening the downward pulse.

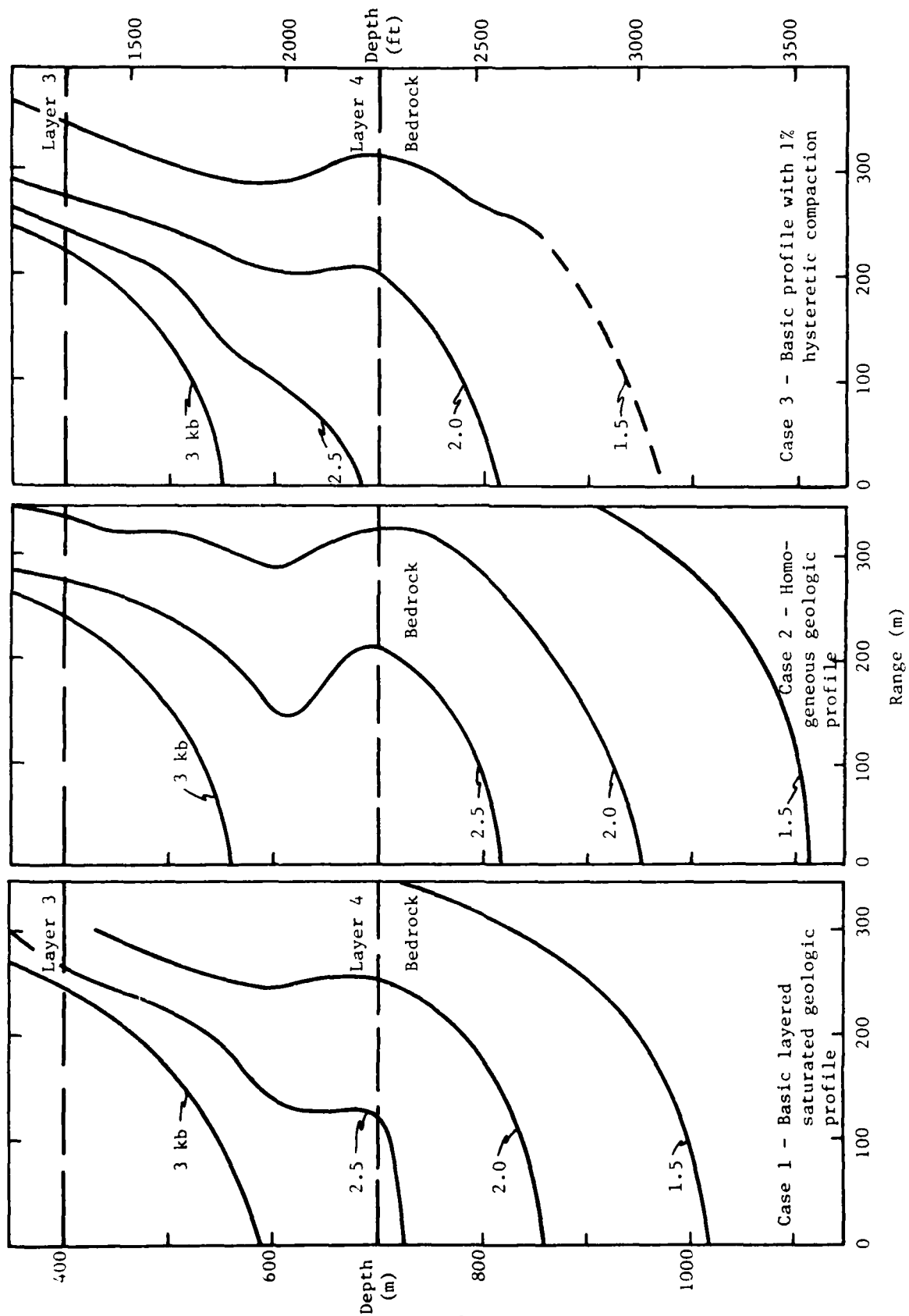


Figure 9. Peak Stress Contours



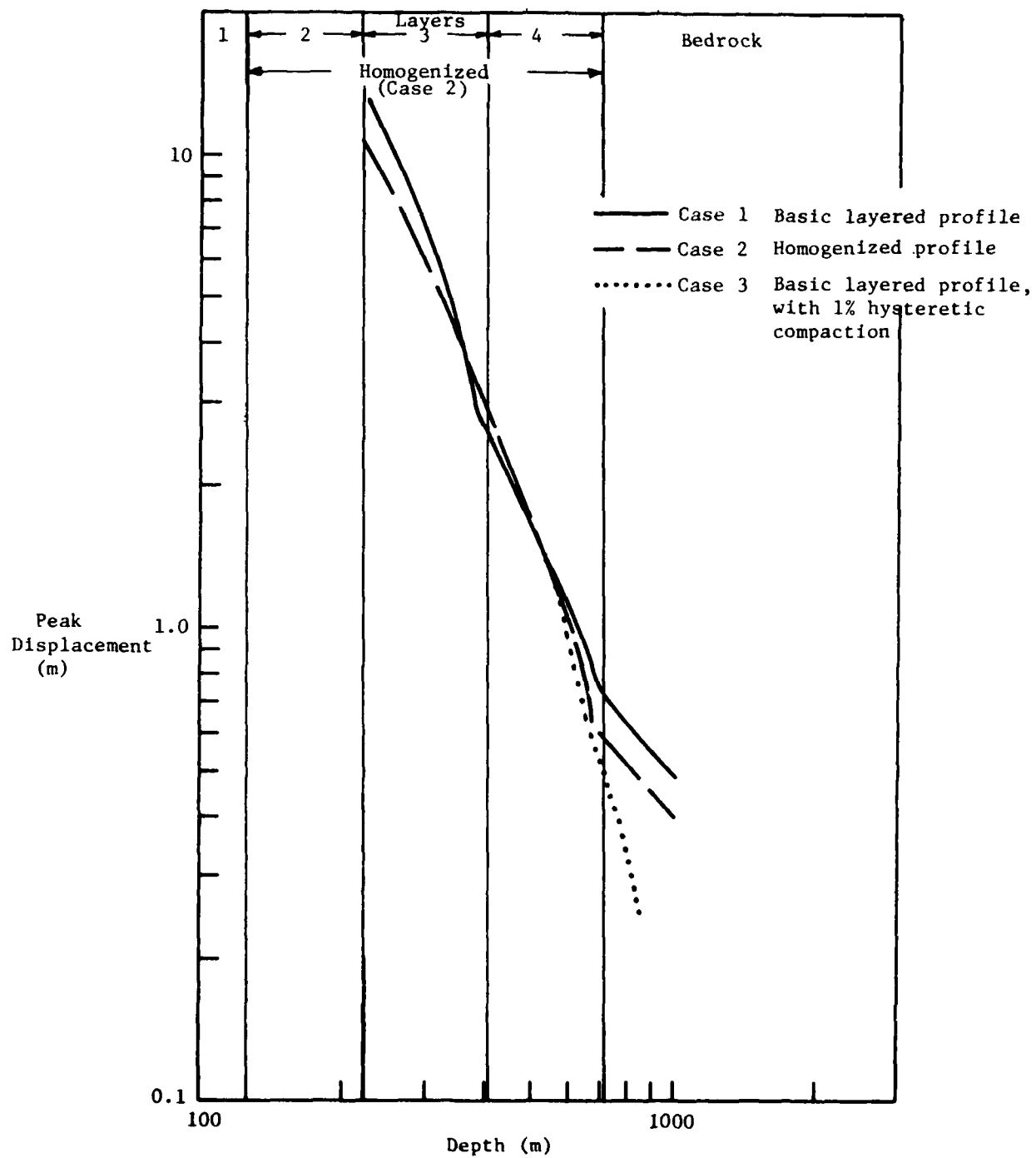
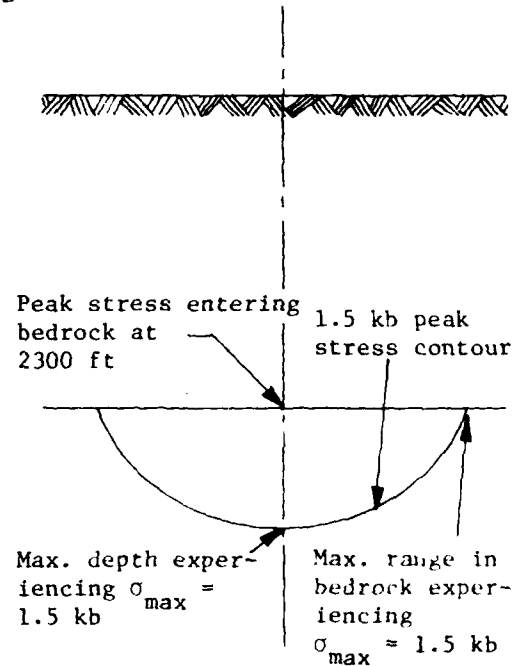


Figure 10. Peak On-Axis Displacement vs Depth.

#### SECTION 4.

#### CONCLUSIONS

The three parameters defined in the sketch are used to summarize key findings of the analyses in the following tabulation.



	Peak Stress Entering Bedrock	Max. Depth Experiencing $\sigma_{\max} = 1.5 \text{ kb}$	Max. Range in Bedrock Experiencing $\sigma_{\max} = 1.5 \text{ kb}$
Case 1. Basic layered, saturated profile	2.6 kb	3345 ft (1020 m)	1150 ft (350 m)
Case 2. Homogenized media above bedrock	2.9 kb	3705 ft (1120 m)	1310 ft (400 m)
Case 3. Same as Case 1, but with 1% hysteretic compaction	2.4 kb	3180 ft (970 m)	1000 ft (305 m)

The *trends* seen in this tabulation are as would be expected; sedimentary layering or hysteretic compaction will indeed reduce stresses on a deep facility beneath a near-surface burst. *However, the differences are relatively small, of the order of 10-15%.*

Futhermore, the calculated maximum depths where 1.5 kb peak stresses are experienced in geologies with saturated, layered soft rocks over deep bedrock correspond roughly with the *deepest* values predicted from empirical data for stress attenuation in *hard rock* (Equation 1).

The following conclusions are drawn from these results:

1. The effects of layering, involving typical differences in properties between sedimentary, saturated soft rock layers, do not substantially reduce peak stresses beneath near-surface bursts.
2. Deep base facilities located in geologies consisting of saturated layers of sedimentary soft rock above deep bedrock (typical of Minuteman sites) would need to be placed at depths equivalent to those required in hard rock geologies.

#### REFERENCES

1. H. F. Cooper, Jr., "Empirical Studies of Ground Shock and Strong Motions in Rock", DNA 3245F, October 1973.
2. H. F. Cooper, C. P. Knowles, and H. Brode, R & D Associates, personal communication.
3. J. Zelasko, Waterways Experiment Station, letter of 21 March 1977 to S. H. Schuster.
4. S. H. Schuster and J. Isenberg, "Equations of State for Geologic Materials", DNA 2925Z, September 1972.

## APPENDIX

### GEOLOGY AND MATERIAL MODELING

#### Case 1. Representative Saturated Layered Geology

The dimensions and properties for the representative saturated layered profile for Case 1 in Figure 1 were constructed using data provided by J. Zelasko of Waterways Experiment Station (WES)<sup>3</sup>. Typically there are several layers at shallow depths; we chose to model these using a single homogeneous surface layer extending down to 125 m because the very strong shock waves from the burst in this region would not be significantly affected by the relatively small impedance mismatches.

The interfaces between layers were assumed to be welded.\*

The soil layers and bedrock were modeled with an updated version of the Schuster-Isenberg<sup>4</sup> equations of state used extensively in nuclear and chemical explosive cratering studies. Basically, the stress-energy-strain behavior is decomposed into a mean stress or pressure relationship plus the deviatoric stress tensor. The mean stress is further decomposed into two terms, i.e.,

$$P = P_s + P_v \quad (A1)$$

where  $P_s$  represents the solid or liquid phases and  $P_v$  the vapor. Hysteresis, low-energy thermal effects, and reversible solid-solid phase changes are incorporated into the calculation of  $P_s$ .

---

\* Differential displacements across interfaces in a layered media pose separate hazards to structures which penetrate through such interfaces; this aspect of siting in layered media was not considered in the current study.

For non-hysteretic materials,

$$P_s = K_m \mu - (K_m - K_o) \mu^* (1 - e^{-\mu/\mu^*}) \quad (A2)$$

where  $K_o$  and  $K_m$  are the initial and maximum bulk moduli,  $\mu^*$  is a material parameter, and

$$\mu = \frac{\rho - \rho_o}{\rho_o} = \text{excess compression}$$

The thermal energy dependence of the solid is incorporated by adding the effect of thermal expansion to  $\mu$  so that it becomes  $\mu + \beta E$ , where  $\beta$  is the coefficient of thermal expansion and  $E$  the energy density. This is equivalent to the Grunisen correction used in other models, with a variable Grunisen gamma. At a solid-solid phase change, the effective  $\mu$  is again altered to reflect the decrease in  $dP/d\mu$ . Hence  $\mu$  is replaced by  $\mu - \mu_\Delta$  where

$$\mu_\Delta = \delta (\mu - \mu_p) \quad (A3)$$

and  $\delta$  and  $\mu_p$  are phase change parameters.

The vapor term,  $P_v$ , is computed using a variable gamma-law gas,

$$P_v = (\gamma - 1) \rho E^* \quad (A4)$$

where

$$\gamma - 1 = .4 + .23 \log \rho + [.35 \log (E^*/\rho) - .464]^2 \quad (A5)$$

and  $E^*$  is an effective energy density,

$$E^* = \begin{cases} (E - E_m) \left[ 1 - e^{-\left(\frac{E - E_m}{E_m}\right)} \right] & E \geq E_m \\ 0 & E < E_m \end{cases} \quad (A6)$$

Incremental deviatoric stresses are computed from changes in the deviatoric strain tensor using the elastic equation

$$d\sigma'_{ij} = -2Gde'_i \quad (A7)$$

where the shear modulus  $G$  is assumed to be constant. The second invariant of the deviatoric stress tensor,  $\sqrt{J_2'}$ , is then compared to a von Mises type plastic yield surface,  $Y$ . If  $\sqrt{J_2'}$  exceeds  $Y$ , the material has yielded and the deviatoric stresses are reduced by the standard Drucker-Prager flow rule, i.e., without volumetric strain.

Values of the constants for the materials in each layer are listed in Table A-1. To assure correctness of seismic speeds in the various layers, the constrained moduli and Poisson's Ratio provided by Zelasko were used to determine the zero pressure moduli in the equations of state. However, the bulk modulus in each layer increased exponentially with compression to a single high pressure ( $> 100$  kbar) value consistent with the available Hugoniot data.

## Case 2. Partially Homogenized Geology

For Case 2, layers 2, 3, and 4 were homogenized and given the weighted average properties for density, bulk moduli, and sound speed shown in Table A-1. To verify that these average properties would give approximately the same waveform incident to the bedrock interface at 700 m depth as the explicitly modeled layer properties used for Case 1, comparative 1-D spherical analyses were run. The results shown in Figure A1 indicate that both models produce the same nominal waveform in a spherically diverging geometry; any differences in the 2-D solutions of Cases 1 and 2 can therefore be attributed to the diffractive effects of the interface planes.

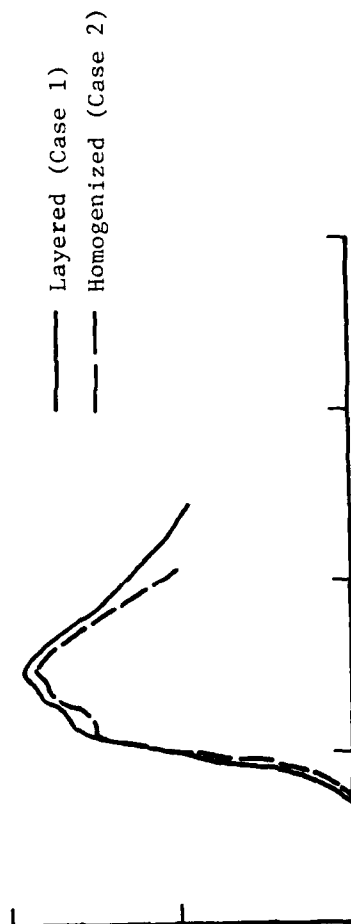


Figure A-1. Stress Profile at 2130 ft (650 m) Obtained from 1-D Spherical Analyses to Assess Effects of Homogenized Properties on Waveforms Incident to the Bedrock Interface.



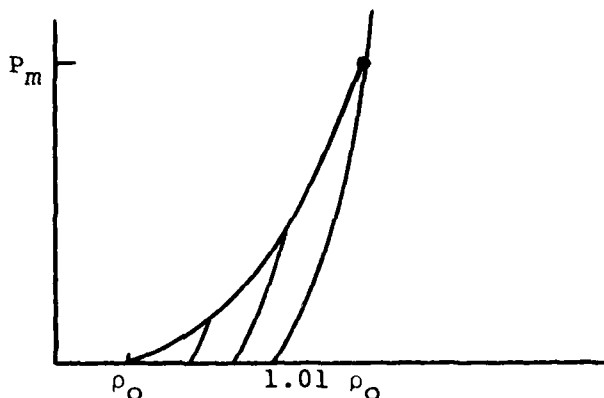
TABLE A-1. EQUATIONS OF STATE CONSTANTS

Parameter	Symbol	Units	Case 1					Bedrock	Case 2 Combined 2-3-4
			Layer	1	2	3	4		
			Depth (m)	0-125	125-215	215-400	400-700	700-1110	1110-2300
			(ft.)	0-410	410-705	705-1310	1310-2300	2300-3600	3600-4100
Initial Density	$\rho_0$	gm/cc		2.11	2.28	2.36	2.64	2.72	2.56
Initial Bulk Modulus	$K_0$	Mb		.06	.08	.13	.25	.42	.18
Maximum Bulk Modulus	$K_m$	Mb		.4	.4	.4	.4	.42	.4
*	$\mu^*$	--		.2	.2	.2	.2	.2	.2
Initial Sound Speed	$C_0$	ft/sec		5,890	7,100	9,545	13,030	16,640	11,230
Coefficient of Thermal Expansion	$\beta$	cc/(cc-Eu)*		3.0	3.0	3.0	3.0	3.0	3.0
Phase Change Parameters	$u_p$ $\delta$			.6588 1.6746	.5351 1.5439	.3672 1.3285	.3258 1.2669	.2868 1.2054	.3672 1.3285
Minimum Energy for $P_y$	$E_m$	Eu		.02	.02	.02	.02	.02	.02
Shear Modulus	$G$	Mb		.0986	.02	.065	.125	.3	.09
Plastic von Mises Limit	$Y$	Mb		$4 \times 10^{-5}$	.0011	.0008	.0016	.004	.0015
Unloading Bulk Modulus ( $P=0$ )	$K_0'$	Mb		.128	.124	.184	.280	---	---
Minimum Loading Pressure to remove all air-filled porosity	$P_m$	Mb		.003	.0045	.0104	.0519	---	---

\*1 Eu = 1 energy unit =  $10^{12}$  ergs

### Case 3. Near-Saturated Layered Geology

Even in nominally-saturated porous media, there is probably a small amount of air entrapped in cracks and pores. To assess the possible importance of such air-filled porosity, 1% hysteretic compaction in Layers 1-4 was allowed in Case 3. To retain the basic characteristics of the Case 1 materials, the loading moduli and hence the sound speeds were not changed. Upon unloading, however,  $K_0$  in Equation A2 was replaced by  $K'_0$  (Table A-1) so that the effective modulus was much higher and the material returned to zero pressure at a density up to 1% higher than initial density, as shown in this sketch.



The value of  $P_m$ , the minimum pressure required to collapse all of the air-filled voids increased with the depth of the layers (Table A-1) to be consistent with the increase in the initial loading moduli.

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